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AN ANALYTICAL EXAMINATION OF IMPEDANCE AND SIGNAL POWER LEVELS ALONG A MULTIPLEX DATA BUS

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REVIEW AND APPROVAL

This technical report has been reviewed and is approved for publication.

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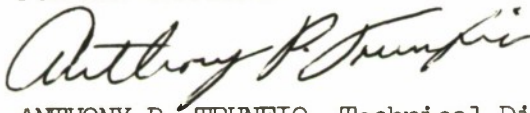KEITH HANDSAKER
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Using MIL-STD-1553 (USAF) as a guide in defining a Multiplex Data Bus, this paper presents in graphical form the results of a series of calculations to determine bus impedance, stub impedance, and signal power levels along a Multiplex Data Bus. The paper also discusses the significance of these parameters in MUX Bus operation.

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TABLE OF CONTENTS

1

LIST OF FIGURES

1.0 INTRODUCTION

Intra-aircraft data transfer using TDM (Time Division Multiplex) Data Bus techniques is a relatively new application of digital data transmission which alleviates problems associated with the installation and operation of complex electronics on-board modern, high-performance aircraft.

A military standard, "Aircraft Internal Time Division Multiplex Data Bus," MIL-STD-1553 (USAF)[1] was published in August 1973 to promote standardization of Multiplex Bus (MUX Bus) implementations. This standard was developed on the basis that it would provide a set of constraints representing the best estimates that could be made at the time. These could be changed as new information became available from analytical and experimental work.

MITRE has been pursuing both analytical and experimental work on multiplex buses to validate the requirements of MIL-STD-1553 (USAF). This report represents the outcome of some of this work. It presents in graphical form the results of a series of calculations dealing with impedances encountered in a MUX Bus system, and discusses their significance in MUX Bus operation.
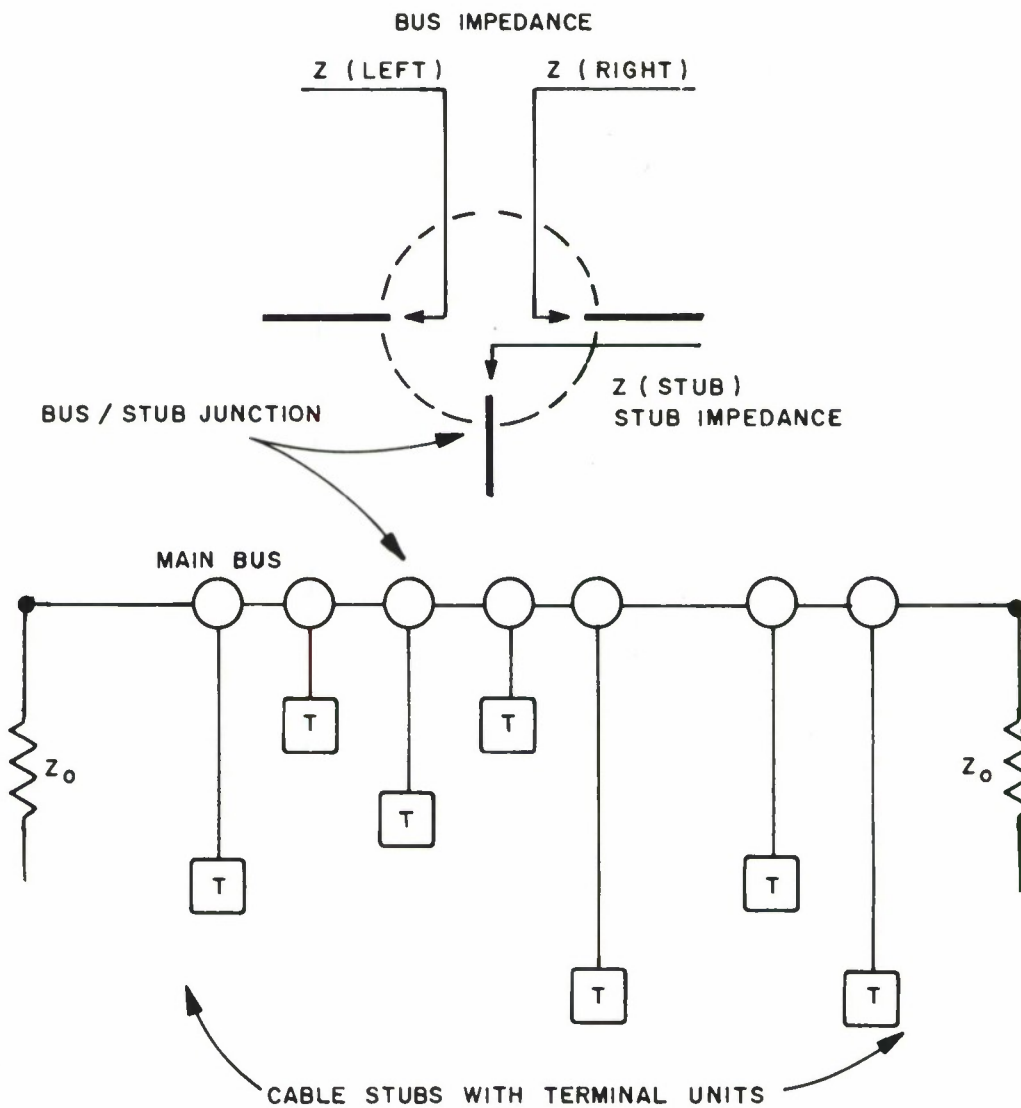
2.0 THE MUX BUS

In a TDM data transmission system of the MIL-STD-1553 (USAF)[1] type, a number of terminal units are connected to a Multiplex Data Bus by means of separate connecting cable stubs (Figure 1). The bus and stubs use cable consisting of shielded twisted pairs, $Z_o = 71$ ohms. In operation, any one terminal unit may be transmitting while all others are receiving. The Standard defines a particular implementation of such a data distribution system and stipulates deliberate impedance mismatches at each bus/stub junction. Hence, the signal power emanating from a transmit stub and reaching the receive stubs along the MUX Bus is significantly affected by the impedances encountered at each bus/stub junction. As shown in Figure 1, at each bus/stub junction the impedance represented by the stub, Z(stub), and the impedances of the bus to the right, Z(right), and to the left, Z(left), will govern the signal transfer and signal power division. Consequently, the values and limits of stub impedance must represent a trade-off between a) high signal transfer from bus to stub, but heavy bus loading (low impedance stub, Z<1000 ohms) and b) low signal transfer from bus to stub, but light bus loading (high impedance stub, Z>1000 ohms). The significance of this trade-off is the main subject of this paper.

In the following pages the results of calculations are presented covering:

(a) stub impedance;

(b) bus impedance; and

(c) signal power division.

In all calculations the cable in bus and stubs between discontinuities was treated as a section of transmission line; the classic

4

BUS IMPEDANCE

Z (LEFT)   Z (RIGHT)

BUS / STUB JUNCTION

Z (STUB)
STUB IMPEDANCE

MAIN BUS

Z_0 Z_0

T   T

T

T

T

T

T

CABLE STUBS WITH TERMINAL UNITS

IA—44,620

Figure I, SIMPLIFIED DIAGRAM, MUX BUS SYSTEM

5

expression for low loss transmission line impedance as a function of cable parameters and load [2] was used (see Appendix, A). The calculations were performed on the MITRE IBM 370/155 facility using the Conversational Programming System.

3.0 STUB IMPEDANCE

3.1 Stub Parameters

The parameters used in the derivation of the impedance of a stub
are shown in Figure 2. Although the figure lumps the cable parameters
to facilitate calculations, the line is actually balanced to ground.
The general case of a stub in the MUX Bus system, as defined by MIL-
STD-1553 (USAF),[1] includes the following:

(a) Two isolation resistors, 54 ohms each. These resis-
tors are denoted by R_I in Figure 2; they were included in all
calculations of stub impedance and positioned in the stub at
the bus/stub junction.

(b) Transformer Near Bus. This transformer was defined
by its winding resistance, R_W, and leakage inductance L_L, its
magnetizing inductance, L_M, and turns ratio, N. The values
for these parameters were chosen from a typical pulse trans-
former (Pulse Engineering, Inc., Type 5163) known to have been
used in a MUX Bus application.

$$R_W = 14 \text{ ohms}$$
$$L_L = 7 \text{ } \mu h$$
$$L_M = 10 \text{ mh}$$

Above values apply to the transformer primary winding. They were
recalculated for the secondary, taking into account the trans-
former turns ratio.

In all calculations, this transformer was positioned
directly adjacent to the isolation resistors. When not used,
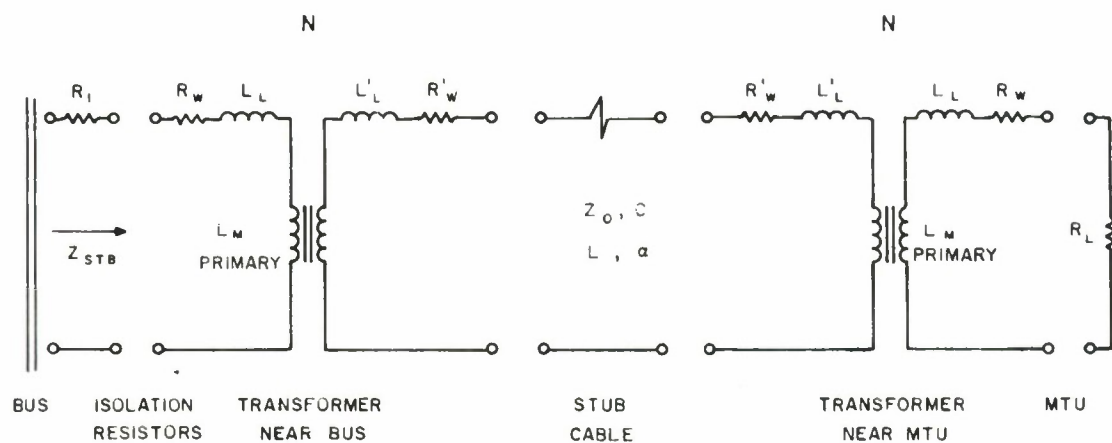the values of R_W, L_L were set to zero, N equal 1, and L_M very
high.

7

Figure 2, STUB PARAMETERS-DERIVATION
OF STUB IMPEDANCE

(c) Cable Stub. When using standard cable, the following
parameters were used.

Z_o = 71 ohms

C = 21 pf/ft

α = 0.0004 nepers/foot, equal to about 0.35 db/100 ft.
(a value obtained from laboratory measurements of
a cable known to be used in a MUX Bus application).

In one set of calculations, a twisted, shielded pair having Z_o =
200 ohms, C = 6.5 pf, and α = 0.0003 nepers/ft. was used for the
stubs only.

(d) Transformer Near MTU (Multiplex Terminal Unit). Simi-
lar considerations and parameters apply here as in (b) above.

(e) Load, R_L. The MTU was represented by a resistor with
value R_L.

3.2 Stub Impedance, No Transformers

Figure 3 shows the impedance of a stub consisting of the iso-
lation resistors and stub cable as a function of stub length and stub
load. In the graphs of this figure, as well as in subsequent figures,
impedance phase angles are shown at significant points.

It is noteworthy that at stub lengths over about ten feet, the
stub impedance is essentially independent of load and varies in magni-
tude from about 400 ohms to 750 ohms at phase angles near -65°.

3.3 Effects of Transformers with 1:1 Turns Ratio on Stub Impedance

In Figure 4 the effects of coupling transformers with 1:1 turns
ratios on stubs 10 feet and 20 feet long are examined. Trace #1 shows
the stub impedance without transformers as discussed in Section 3.2 above.

9
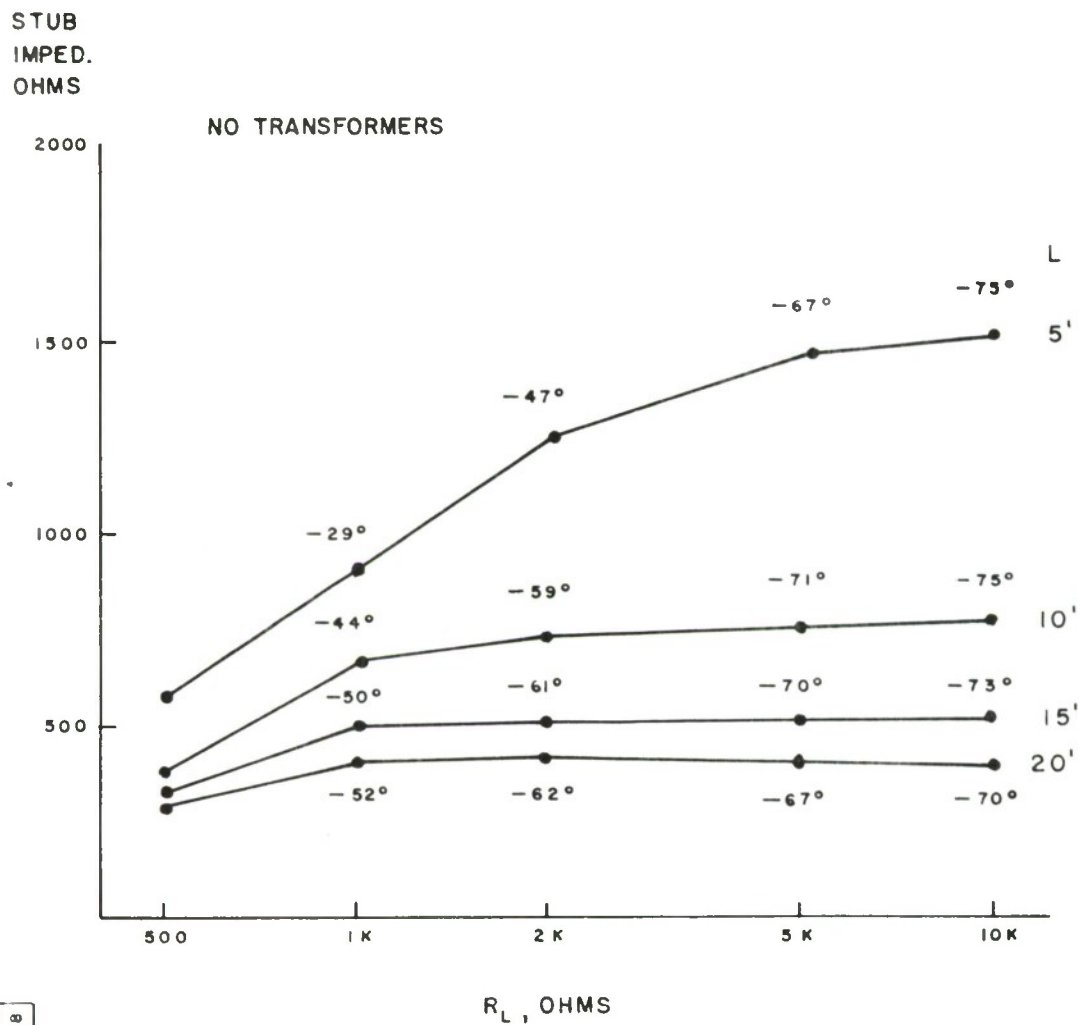
Figure 3, STUB IMPEDANCE VS. LOAD AND LENGTH

Figure 4. EFFECTS OF 1:1 TRANSFORMER ON STUB IMPEDANCE

In trace #2 a 1:1 Transformer near MTU was added.

Trace #3 shows stub impedance with a 1:1 Transformer near Bus.
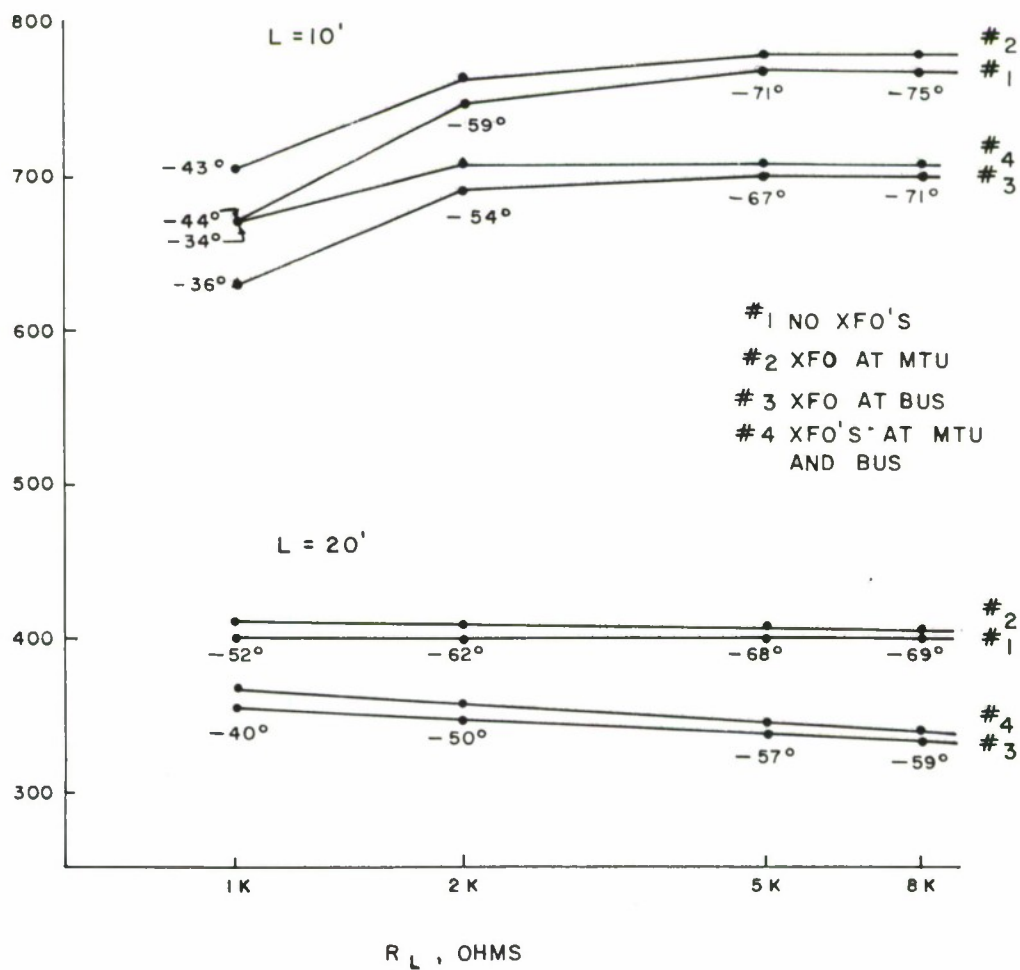
Trace #4 shows stub impedance with two 1:1 transformers, one near bus, the other near MTU.

Comparing traces #1 vs #2 and #3 vs #4, it seems that at the MTU end of the stub, a coupling transformer with 1:1 turns ratio has little influence on stub impedance as seen from the bus. The chief purpose of a transformer near the MTU may be to preserve MUX Bus balance with respect to ground, and with other turns ratios, to serve as an impedance matching device.

Comparing traces #1 vs #3 and #2 vs #4, it is evident that the transformer with 1:1 turns ratio near the bus end of the stub lowers the stub impedance by about 15 percent, or from 400 ohms to about 333 ohms in the case of a 20 foot stub.

As will be shown later, a stub with an impedance near or below 400 ohms represents an undesirably heavy load on the bus, when considering transmit stub loading and the effects of power division at the remaining stubs.

3.4 Stub Impedance - Transformer with 1.4:1 Turns Ratio

The use of a 1.4:1 transformer near the bus raises the stub impedance to about 700 ohms in a 20 foot stub (Figure 5); for stubs of ten feet and longer, the stub impedance does not vary by more than a factor of two as the load resistance is changed from 500 ohms to 10,000 ohms. Stubs shorter than ten feet could conceivably be connected to the bus without transformers to match the impedance values of the longer stubs if the waveforms proved satisfactory.

12
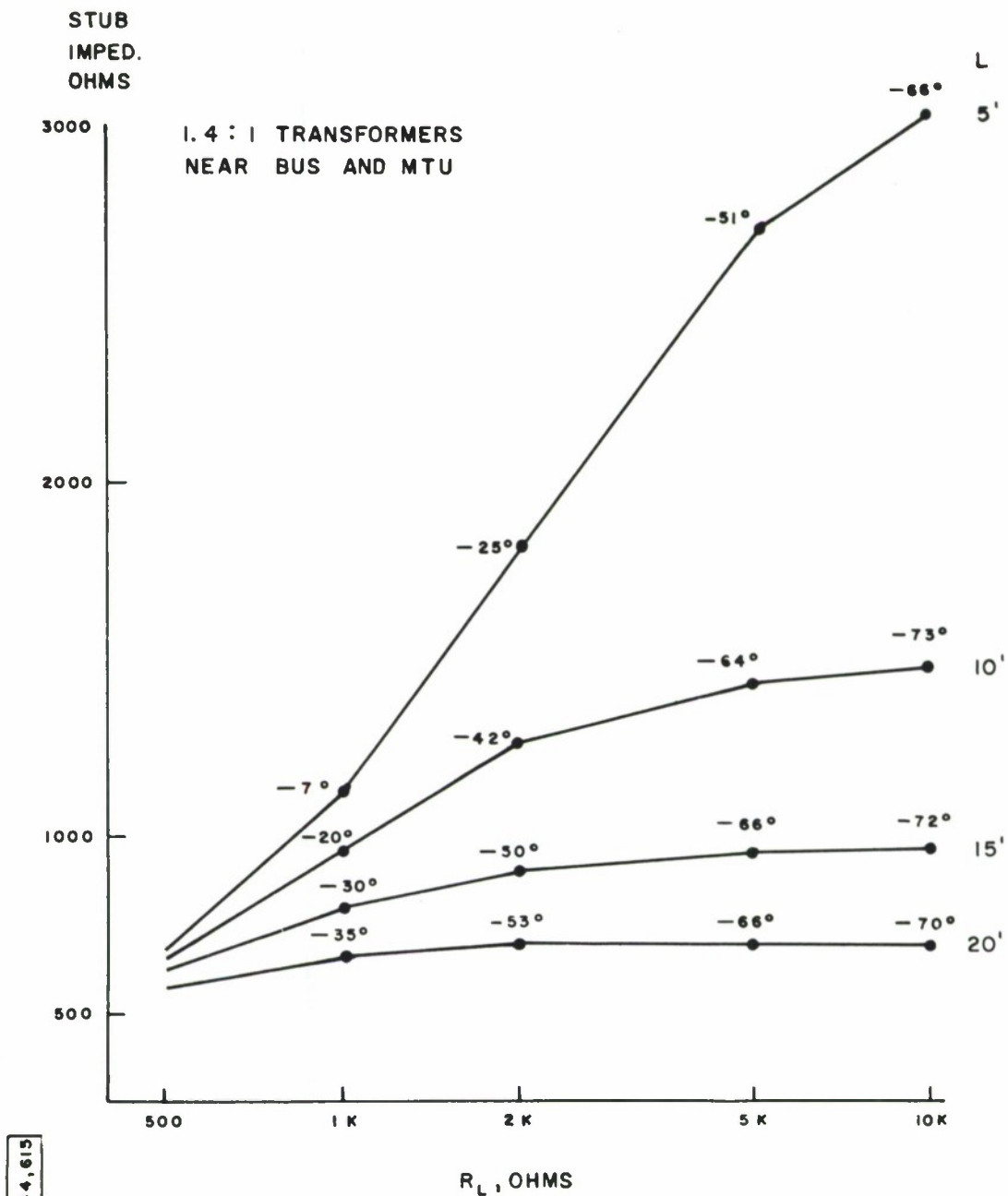
Figure 5, STUB IMPEDANCE VS. LOAD AND LENGTH

3.5 Stub Impedance - Transformer with 2:1 and 2.5:1 Turns Ratio

At transformer turns ratios of 2:1 (Figure 6) and 2.5:1 (Figure 7), stub impedance is further increased but the variations in stub impedance between short stubs and long stubs has risen to a point where it may be desirable, and probably necessary in the case of the 2.5:1 transformer, to use a lower turns ratio for shorter stubs if R_L exceeds 500 ohms.

3.6 Stub Impedance - 200 Ohm Cable

As an alternate way to achieve the proper mismatch between the stub and the bus, consideration has been given to changing the twisted pair of just the stubs to a cable with higher characteristic impedance. This could be used without a matching transformer at the stub/bus junction. Since the twisted, shielded pair is available with a characteristic impedance of 200 ohms, and a cable capacitance of 6.5 pf/ft, a set of calculations was obtained using these parameters. A 1.4 to 1 coupling transformer was used near the MTU only to permit the MTU to present a balanced load to the stub. (With a turns ratio of 1.4 to 1, the impedance changes at a 2 to 1 ratio and is easily calculated for other values of R_L.)

It is apparent from Figure 8 that near a load resistance of 3000 ohms, stub impedances are over 1000 ohms and in a comfortable range when considering long or short stubs. Since no transformer is used near the bus, stubs using 200 ohm cable may reduce installation and maintenance problems without causing unnecessarily heavy electrical loads on the MUX Bus.
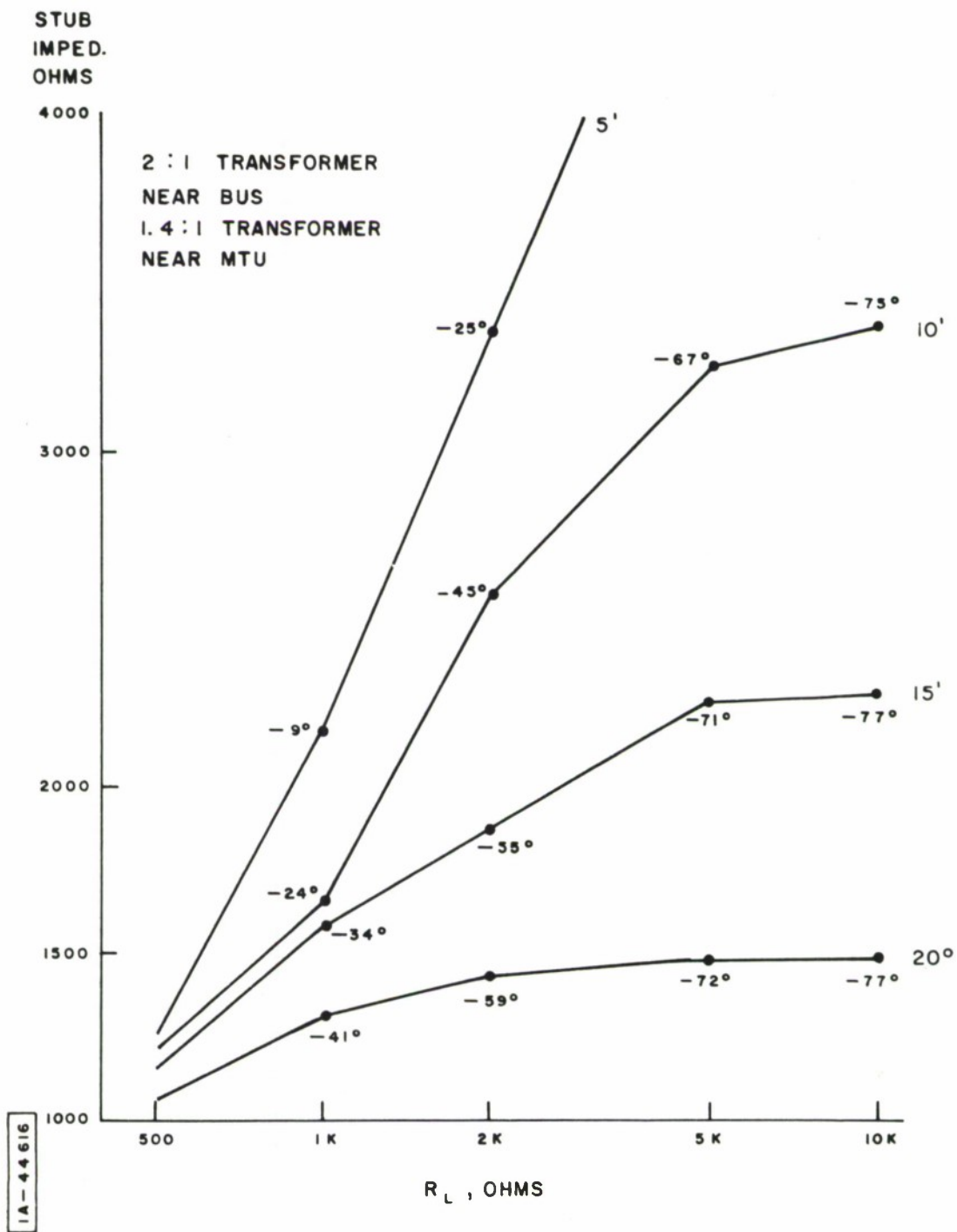
Figure 6, STUB IMPEDANCE VS. LOAD AND LENGTH

STUB
IMPED.
OHMS

2.5 : 1 TRANSFORMER
NEAR BUS
1.85 : 1 TRANSFORMER
NEAR MTU

5'

10'

−12°

−74°

15'

−29°

−64°

−40°

−67°

−75°

20'

0°

−10°

−18°

−47°

−25°

R_L, OHMS

Figure 7, STUB IMPEDANCE VS. LOAD AND LENGTH

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STUB
IMPED.
OHMS

3000

200 Ω CABLE
NO TRANSFORMER
NEAR BUS
I.4 : I TRANSFORMER
NEAR MTU

5'

−22°

−59° 10'

2000

−40°

−66° 15'

−51°

−70° 20'

−7°
−16°

−57°

1000

−24°

−32°

0°

500

−12°

IA − 4461 4

500   I K   2 K   5 K   10 K

R_L , OHMS
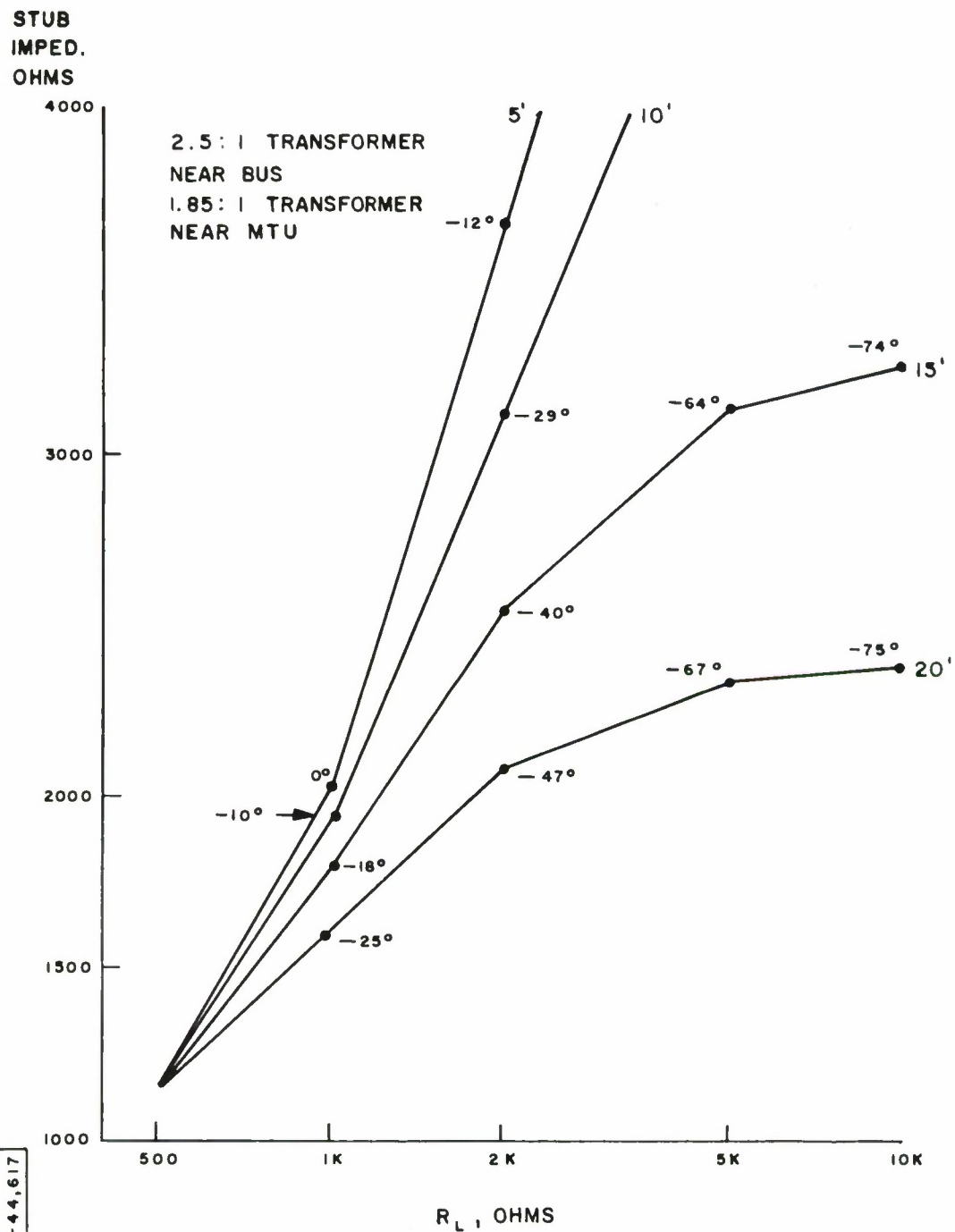
Figure 8, STUB IMPEDANCE VS. LOAD AND LENGTH

17

4.0 BUS IMPEDANCE

The impedance of a MUX Bus at a specific point along its length, as seen by a transmit stub connected to the bus, cannot be assumed to measure half the value of each terminating resistor 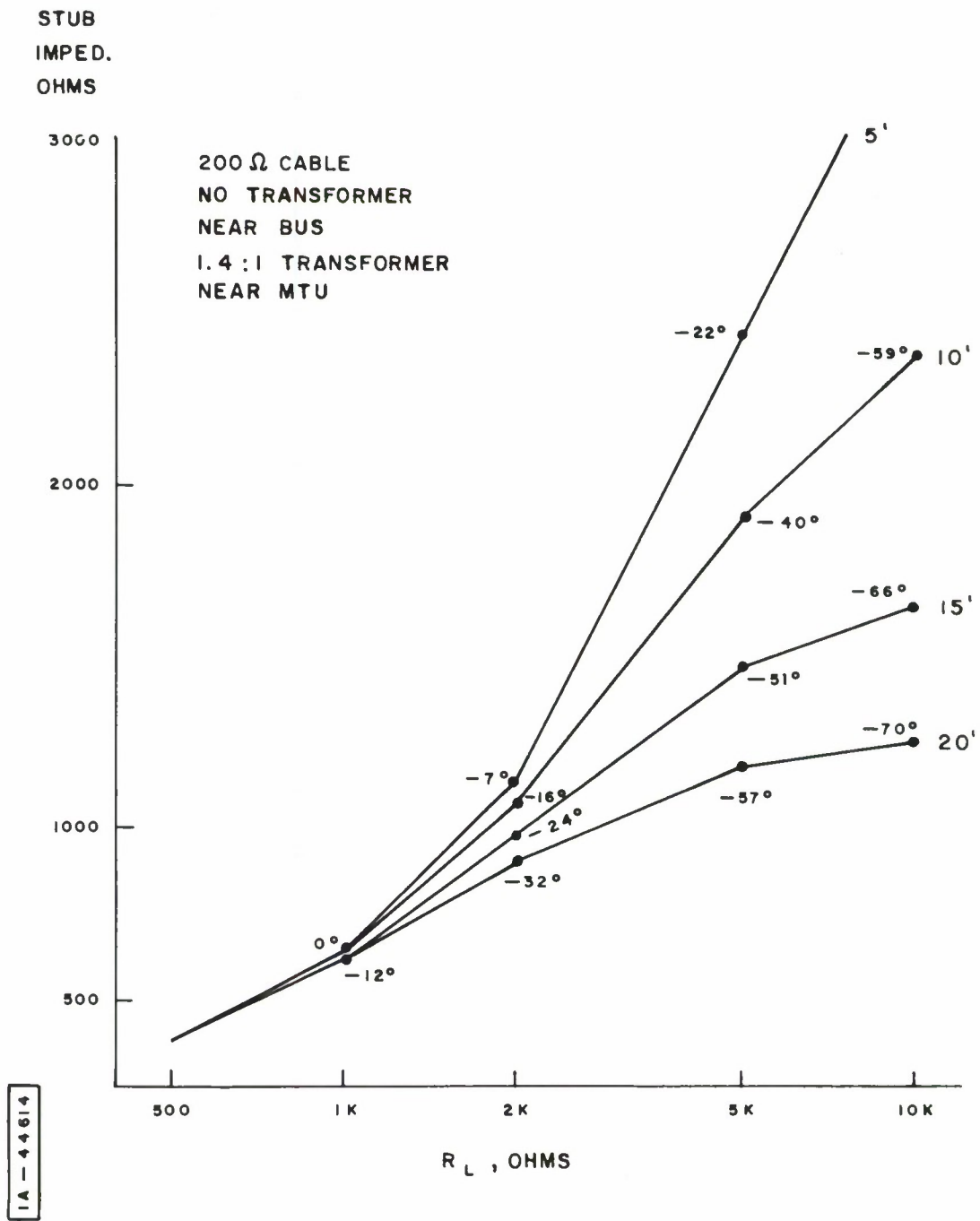at the ends of the bus. It will be shown that a MUX Bus, even lightly loaded by cable stubs, presents impedances to its stubs which vary significantly along its length.

Calculations were carried out, assuming a MUX Bus 300 feet long, with 32 receiving stubs (of equal impedance for any single graph), spaced at random distances between 2 and 15 feet along the bus.

4.1 Derivation

The MUX Bus impedances were derived by examining a bus section and its load in successive steps beginning at one end of the bus.

At the first section of the bus, represented by a bus section of length $L(0)$ loaded by the terminating resistor, Ro, (Figure 9, a), the bus impedance, $Z(0)$, is equal to Ro since any length of transmission line terminated in its characteristic impedance is substantially a resistance of value Ro.

Adding a receive stub, $Z(stub)$, and a section of bus of length, $L(1)$,(Figure 9, b), the bus impedance at junction 1, $Z(1)$, is equal to $Z(0)$ in parallel with $Z(stub)$, as transformed through a bus section of length $L(1)$. Similarly, $Z(2)$ at junction 2 (Figure 9, c) is equal to $Z(1)$ again in parallel with $Z(stub)$, as seen through bus section of length $L(2)$.

18

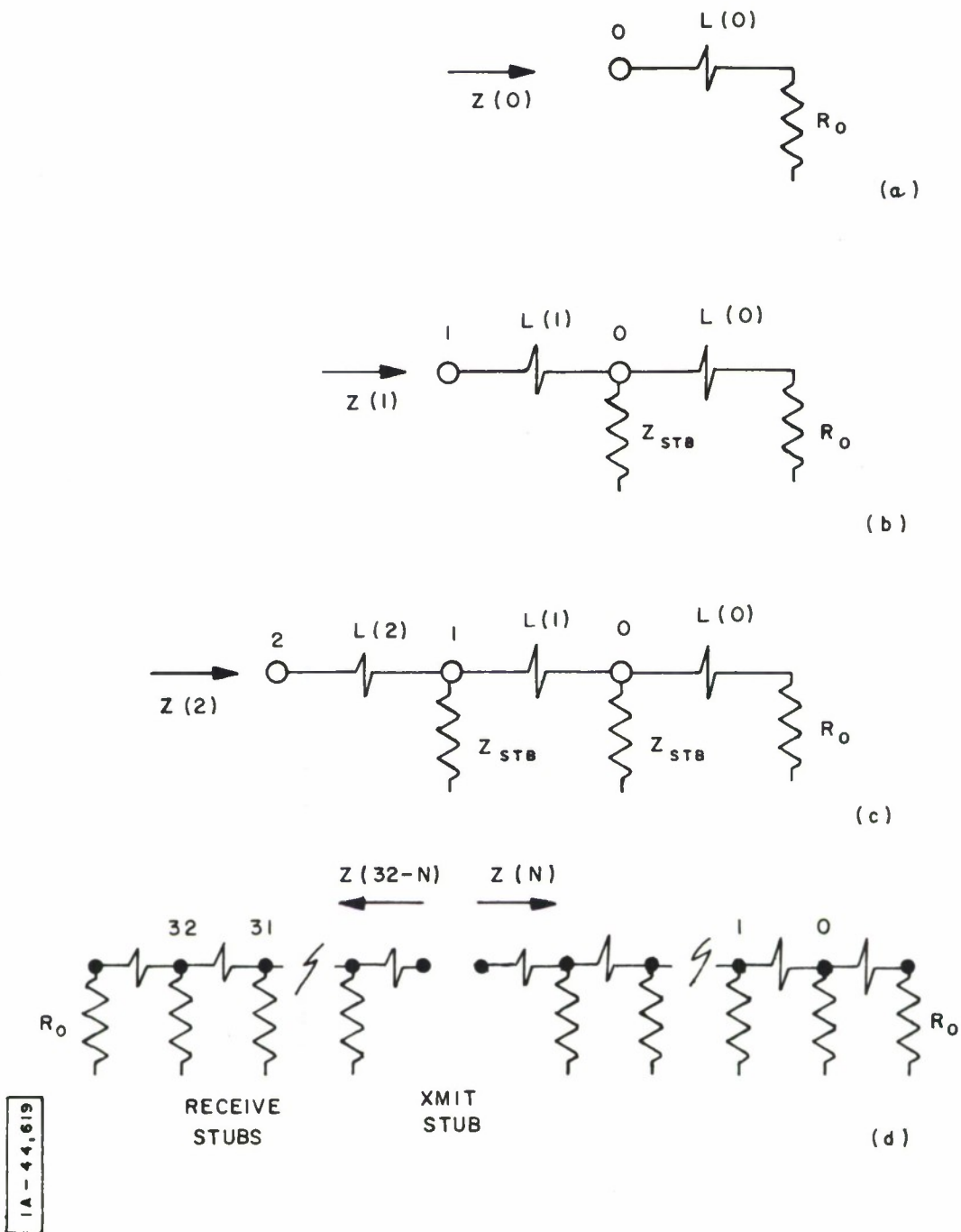Figure 9, DERIVATION OF BUS IMPEDANCE

19

4.2   Bus Impedance, Measuring One Side of Bus

Starting with Stub 1 and continuing the process above for 32
stubs, the graphs in Figure 10 were obtained. For example, it is
apparent from Figure 10 that looking into one side of a MUX Bus with
10 randomly spaced stubs of 2000 ohms each, a bus impedance of 53
ohms will be seen. The same bus, with 10 stubs of 333 ohms each, will
have an impedance of 25 ohms.

4.3   Bus Impedance, Transmit Stub Load

The load which a transmit stub (stub N) sees when feeding a MUX
Bus with 32 stubs can be calculated by placing the impedance of a bus
with N stubs, in parallel with a bus with (32-N) stubs (Figure 9, d).
This was done to produce the information in Figure 11 from that of
Figure 10. For example, Figure 11 reveals that a transmit stub in
position 10 on a MUX Bus, i.e., feeding 10 receive stubs to the left
and 22 receive stubs to the right, is loaded by 27.5 ohms when all
receive stubs are 2000 ohms, or 15.5 ohms when all receive stubs are
333 ohms.

It should be noted that Figure 11 does not necessarily represent
a worst case load condition. Referring to Figure 10, it may be seen
that a transmit stub feeding a shorter MUX Bus, one that has 10 stubs
to the left and 10 stubs to the right, will see a load of only 26.5
ohms (½ of 53 ohms) and 12.5 ohms (½ of 25 ohms), respectively, in
the cases cited above.

20

BUS
IMPED,
OHMS

$Z_{STB} = 4000\,\Omega$

$Z_{STB} = 2000\,\Omega$

$Z_{STB} = 1500\,\Omega$

$Z_{STB} = 1100\,\Omega$

$Z_{STB} = 700\,\Omega$

ALL STUB IMPEDANCE ANGLES = 65°

$Z_{STB} = 400\,\Omega$
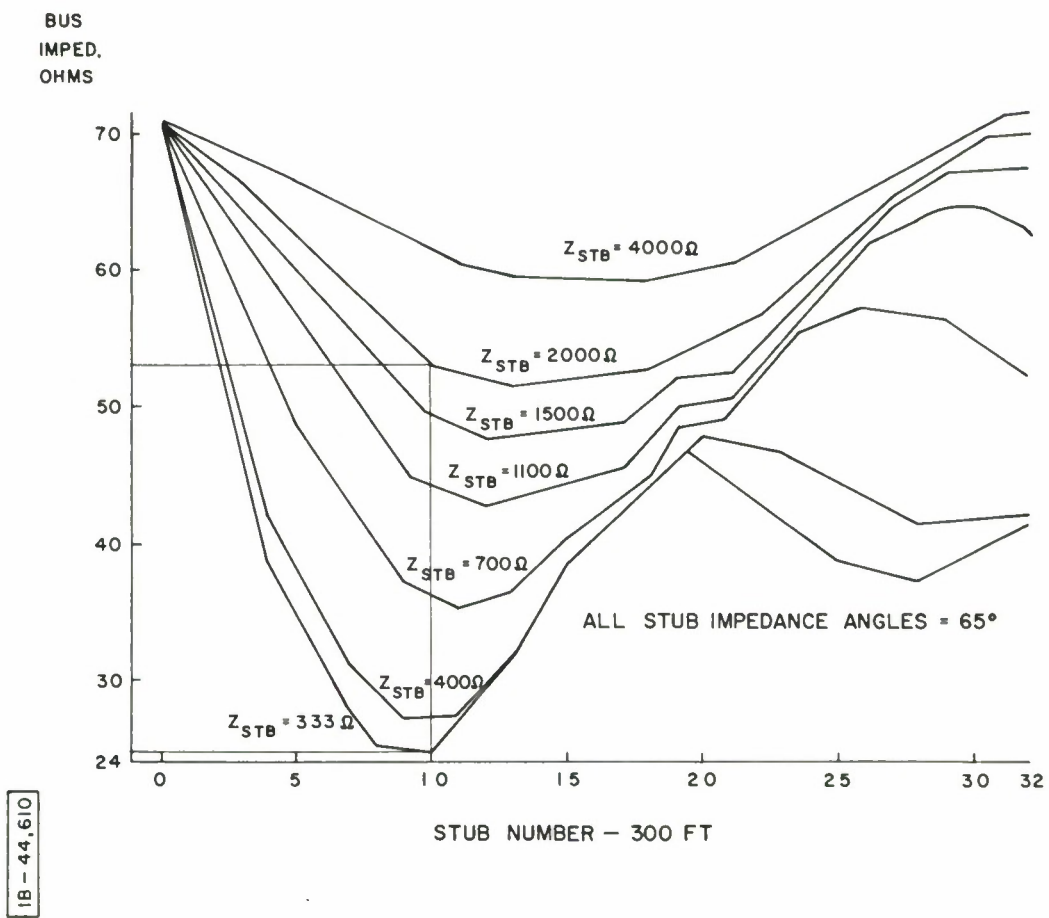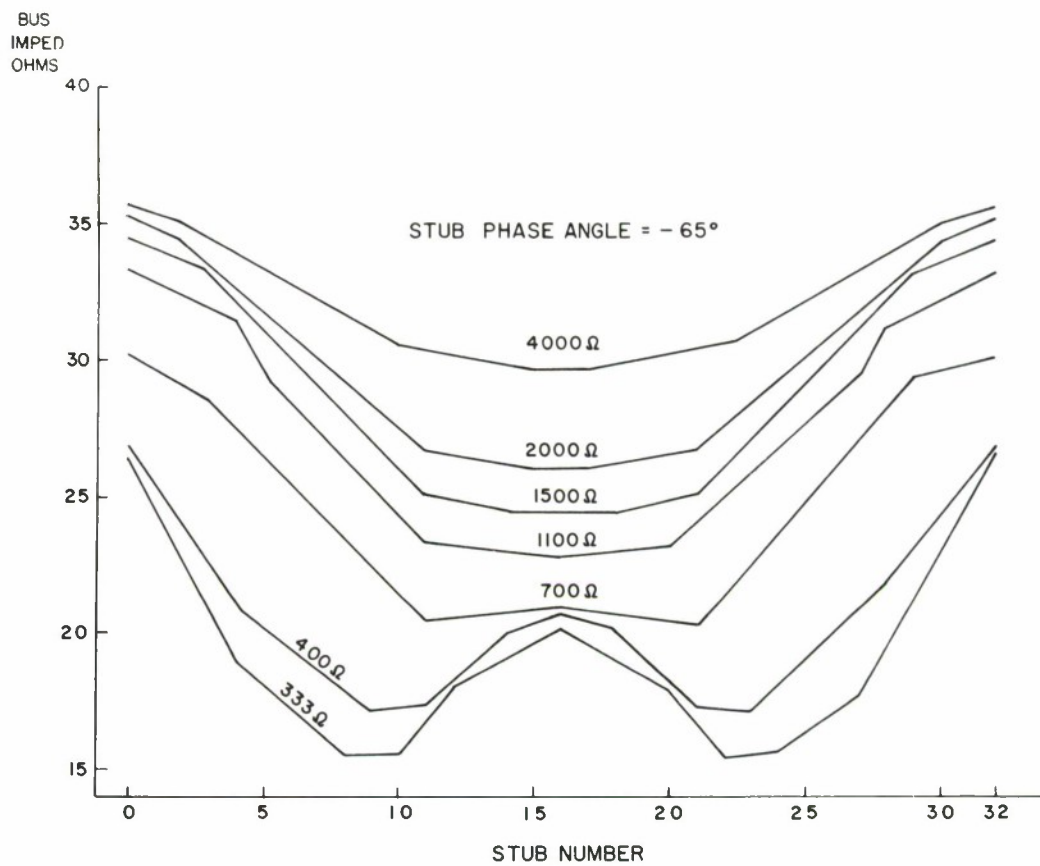
$Z_{STB} = 333\,\Omega$

STUB NUMBER — 300 FT

1B — 44,610

Figure 10, BUS IMPEDANCE VS. NO OF STUBS MEASURING
ONE SIDE OF BUS

21

Figure II, BUS IMPEDANCE VS. STUB POSITION AND IMPEDANCE
ALONG 300 FT BUS

5.0 SIGNAL POWER LEVELS

Knowing the impedance of a stub (Section 3), and the impedance
of the bus at each bus/stub junction (Section 4), one can estimate
the signal power losses which occur in a MUX Bus system.

5.1 Transmit Stub Losses

Discounting obvious and substantially constant losses in a trans-
mit stub, such as may occur in a coupling transformer and the cable
itself, the two isolation resistors of 54 ohms each cause a rather
significant transmit power loss. This loss varies as the bus imped-
ance changes at each bus/stub junction as a function of stub impedances
and location along the MUX Bus (see Figure 11). The transmit power
loss due to the isolation resistors ranges from 6 dB, in the unlikely
event that the transmit stub feeds a bus without any receive stubs
and sees a load of 35.5 ohms, to about 10 dB when the bus is loaded
with many low impedance stubs (Figure 12).

5.2 Receive Stub Losses

The signal power which reaches a receive stub from the bus is a
function of the impedances of bus and stub at each bus/stub junction.
It can be shown (see Appendix, B) that a reasonable approximation of
signal power division is given by

$$P(stub) = P(bus) \frac{Z(bus) \cos \theta}{Z(stub)}$$

where θ is the phase angle of the stub impedance. The signal power
on the bus, $P(bus)$, is the power level on that section of the bus

23
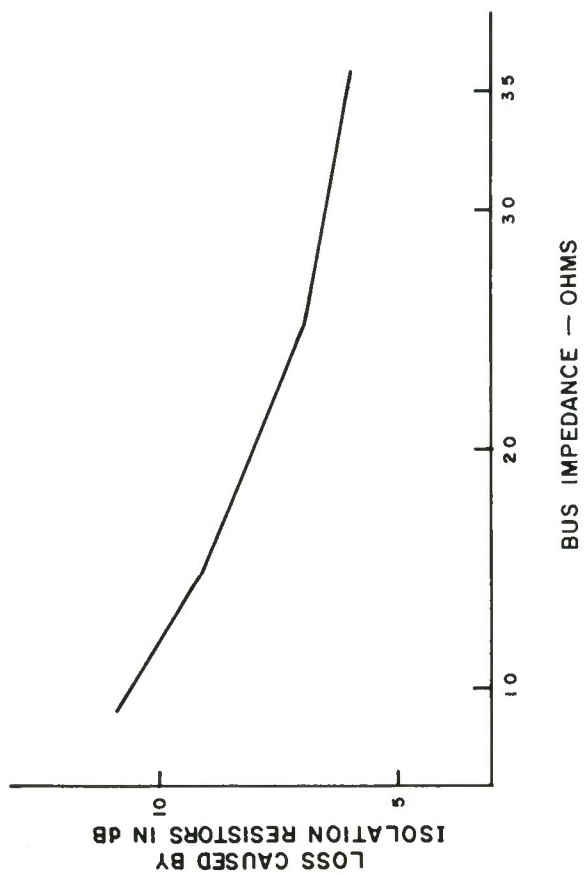
Figure 12, TRANSMIT POWER LOSS DUE TO
TWO 54 OHM ISOLATION RESISTORS

which immediately precedes the junction from the direction of the signal source. Also, at the next section of bus, the signal power is reduced by the power diverted to the previous receive stub (see Figure 13), or

$$P_2(bus) = P_1(bus) - P(stub).$$

Given a certain signal power level, P, at the bus/stub junction of the transmit stub, the ratio of signal power diverted to each receive stub with respect to signal power, P, is shown in Figure 14, when the transmit stub is at the center of the MUX Bus, and in Figure 15 when the transmit stub is at one end.

Figure 15 shows that loading a MUX Bus with stubs of low input impedance (400 ohms and lower), particularly when the bus is long and has many stubs, reduces the signal power at stubs distant from the transmitter to undesirably low levels.[*]

From Figures 14 and 15 it is evident that loading a MUX Bus with stubs of high impedance (2,000 ohms and higher) does not assure optimum MUX Bus operation. At light loads very little power reaches the receiver unit, and most of it is dissipated uselessly in the two terminating resistors at the ends of the MUX Bus.

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* Similar conclusions were reached on the basis of laboratory experiments performed at MITRE, with a recommendation to limit, in a MUX Bus using direct coupled stubs or 1:1 transformers, the total length of cable in bus plus stubs to about 350 feet.
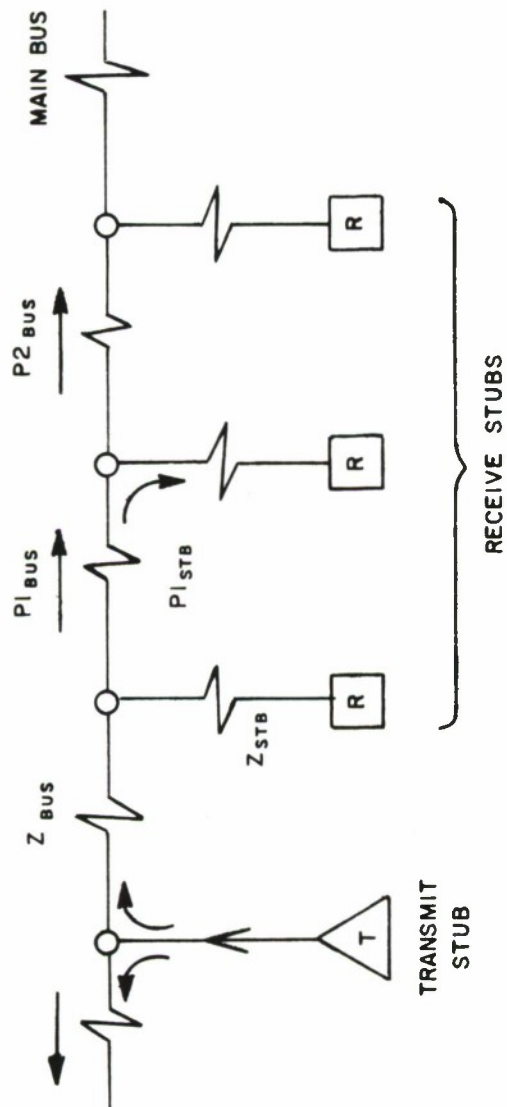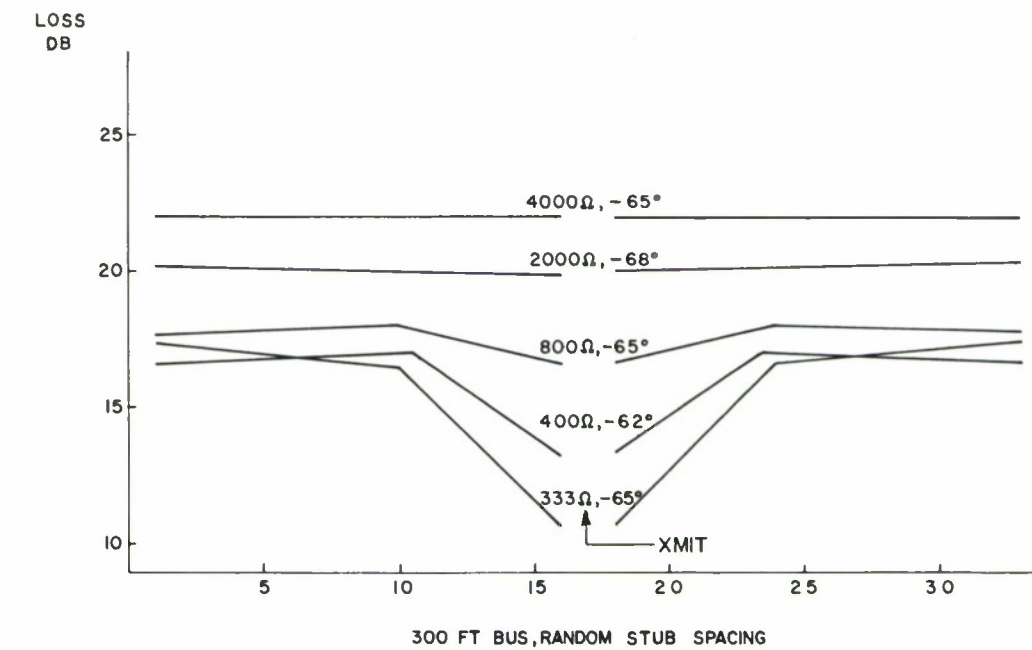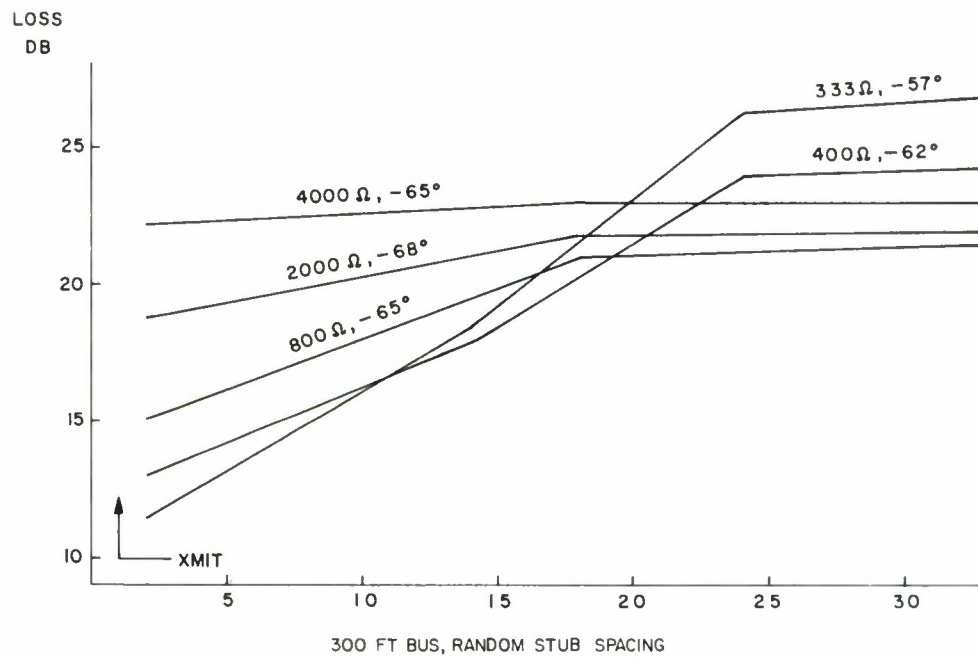
Figure 13, DERIVATION OF SIGNAL POWER LEVELS

Figure 14, RECEIVE POWER LOSS VS. STUB NUMBER

IB – 44,613

Figure 15, RECEIVE POWER LOSS VS. STUB NUMBER

6.0 CONCLUSIONS

The information presented in the graphs of the preceding pages was generated to provide a better understanding of the significance of a range of stub impedances and bus impedances in MUX Bus operation.

It may be in order to confirm the above data through laboratory measurements on physical MUX Bus models. However, discounting other constraints (reflections, SWR, parameter tolerance deviations, etc.), the following preliminary conclusions may be drawn:

(a) Stubs having a low impedance (500 ohms or less) should be avoided, since the resulting heavy bus loading causes excessive losses in a transmit stub, and undesirable receive power losses to distant receivers.

(b) Coupling of stub to the bus by a transformer with 1:1 turns ratio may deteriorate bus operation over directly coupled stubs by further lowering the stub impedance and by possibly adding detrimental noise pick-up through the transformer.

(c) Stubs having a high impedance (1,800 ohms or more) represent a light bus load. Less signal power is diverted from the bus to the receive stubs with a resulting deterioration in MUX Bus signal-to-noise ratio of 2 to 6 dB over receive stubs with impedances near 1000 ohms. Also, the need for differing turns ratios in coupling transformers at the bus/stub junction, in order to keep these losses to a reasonable limit with short and long stubs, may present an installation and supply problem.

(d)   Stubs having an input impedance between 750 and 1,500 ohms present a viable compromise. For example, a MUX Bus system using a 1.4 to 1 turns ratio transformer at the bus/stub junction for stubs longer than ten feet, and no transformer for shorter stubs (direct connection, with isolation resistors near junction), would meet this requirement (see Figures 3 and 5). Also, serious consideration may be given to stubs using 200 ohm cable with direct connection to the main bus and a load resistance near 2000 ohms (see Figure 8).

APPENDIX

A. Input Impedance of Low Loss Transmission Line

The expression for the input impedance of a low loss transmission
line as a function of cable parameters and load is

$$ZIN = \frac{ZL + \alpha\ell + j(1 + ZL\alpha\ell)\tan\beta\ell}{1 + ZL\alpha\ell + j(ZL + \alpha\ell)\tan\beta\ell} \tag{1}$$

where

ZIN = Normalized impedance looking into transmission line, Z(in)/
Zo

ZL = Normalized load impedance, Z(load)/Zo

Zo = Characteristic impedance of cable

α = Attenuation constant, R/2Zo, nepers/foot

R   = Resistance of transmission line cable

ℓ = Length of line, feet

β = Propagation angle, ωZoC, radians

ω = $2\pi f$; calculations were performed at a data rate simulated
by f = 1 MHz.

C   = Capacitance of cable.

Since in most calculations the transmission line load was a
transformer or another section of transmission line, expression (1)
was expanded to provide for Z(load) to be a complex quantity

$$ZL = RZL + jIZL \tag{2}$$

denoting RZL and IZL as the normalized real and imaginary components
of the load impedance.

31

Hence, in computing all MUX Bus system impedances, the computer was programmed to treat the transmission line sections in main bus and stubs as

$$ZIN = \frac{RZL - IZL\alpha\ell\tan\beta\ell + \alpha\ell + j(IZL + (1 + RZL\alpha\ell)\tan\beta\ell)}{1 + RZL\alpha\ell - IZL\tan\beta\ell + j(IZL\alpha\ell + (RZL + \alpha\ell)\tan\beta\ell)} \qquad (3)$$

B. __MUX Bus Signal Power Division__

At any bus/stub junction the signal power on the bus is

$$P(bus) = E\ I(bus)\ \cos\phi \qquad (1)$$

and the power reaching the stub is

$$P(stub) = E\ I(stub)\ \cos\theta \qquad (2)$$

Hence, the power ratio is:

$$\frac{P(stub)}{P(bus)} = \frac{E\ I(stub)\ \cos\theta}{E\ I(bus)\ \cos\phi} \qquad (3)$$

Since calculations for bus impedance (Section 4) showed that angle ϕ rarely exceeded 15°, and the value of $\cos15^\circ$ is 0.966, the bus was considered substantially resistive ($\cos\phi = 1$) and above expression could be reduced to:

$$P(stub) = P(bus)\ \frac{Z(bus)\ \cos\theta}{Z(stub)} \qquad (4)$$

32

REFERENCES

1. MIL-STD-1553 (USAF) Aircraft Internal Time Division Multiplex
    Data Bus, 30 August 1973.
2. Reference Data for Radio Engineers, ITT.